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Hypervelocity Impact Testing of Space Station Freedom Solar Cells

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Abstract

Solar array coupons designed for the Space Station Freedom Electrical Power System were subjected to hypervelocity impacts using the HYPER facility in the Space Power Institute at Auburn University and the Meteoroid/Orbital Debris Simulation Facility in the Materials and Processes Laboratory at the NASA Marshall Space Flight Center.

At Auburn, the solar cells and array blanket materials received several hundred impacts from particles in the micron to 100 micron range with velocities typically ranging from 4.5 to 10.5km/s. This fluence of particles greatly exceeds what the actual components will experience in Low Earth Orbit. These impacts damaged less than 1% of total area of the solar cells and most of the damage was limited to the cover glass. There was no measurable loss of electrical performance. Impacts on the array blanket materials produced even less damage and the blanket materials proved to be an effective shield for the back surface of the solar cells.

Using the light gas gun at MSFC, one cell of a four cell coupon was impacted by a 1/4" spherical aluminum projectile with a velocity of about 7km/s. The impact created a neat hole about 3/8" in diameter. The cell and coupon were still functional after impact.

Introduction

The solar arrays of the Space Station Freedom (SSF) are being designed to operate in low earth orbit for 15 years. In this environment, the arrays will experience hypervelocity impacts from micrometeoroids and orbital debris. Since most of these impacts will be from particles with sizes in the micron and sub-micron range, the HYPER facility at Auburn University was used to shoot 100 micron (mesh size) particles at SSF solar array components.

The SSF solar array consists of 8cm x 8cm solar cells mounted on a flexible blanket. The silicon solar cells are .008" thick and are covered with a .005" thick glass cover. This is mounted on a blanket made of three layers of Kapton[1] film each .001" thick and one layer of glass scrim cloth, all of which are bonded together with layers of adhesive. For these tests a coupon consisting of four cells mounted in a square formation was used.

Test Facility

The Hypervelocity Impact Facility (HYPER) at Auburn University uses an electro-thermal accelerator technique.[1] The projectiles are

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[1] Kapton® is a registered trademark of E.I. du Pont Nemours & Co., Inc.

accelerated by an extremely hot plasma which is generated by discharging a very large capacitor bank across an aluminum foil. The current pulse, which is on the order of 1 million amps, vaporizes the aluminum foil and the resulting gas explodes down a tube. This, in turn accelerates the projectile load which has been coated onto a thin film adjacent to the foil. During acceleration the projectiles are shattered or ablated into numerous smaller particles. As a result, only the maximum size of the particles can be predicted. Furthermore, these particles obtain a wide distribution of velocities which is related to the mass of the projectile load. Although the particle sizes and velocities can not be known *a priori*, they can be determined to some extent during the test. Instrumentation and cameras have been installed which allow for measurement of the X & Y coordinates of each impact, the number of impacting particles, the velocity of some particles, the duration of the optical flash after impact, and the approximate cone angle of the ejecta. In addition, a very thin Mylar[2] film can be placed up range of the target to record the diameter of the impacting projectiles. Since the ballistic limit of the Mylar is greatly exceeded, the projectile can pass unaffected through the film leaving a neat hole.

The light gas gun at MSFC is well described in Reference 3. This facility has the following capabilities:

Projectile Mass	4 mg - 2.1 g
Projectile Size	2.5 - 12.7 mm
Velocity	2 - 7.5 km/s

For these tests a mask was placed in front of the solar cell coupon to minimize damage from sabot impact.

[2] Mylar® is a registered trademark of E.I. du Pont Nemours & Co., Inc.

Test Procedure

Using HYPER at Auburn University, three different type particles were used. One hundred micron (mesh size) aluminum oxide (Al_2O_3), one hundred micron olivine ($[FeMg]_2SiO_4$), and 400 micron aluminum oxide. These projectiles were fired at the front surfaces of three solar cells and at the back surface of the forth.

Test Matrix

Test #	Cell #	Surface	Projectile
C19	11-219	Front	100 mm Al_2O_3
C20	11-221	Front	400 mm Al_2O_3
C21	11-232	Front	100 mm $[FeMg]_2SiO_4$
C67	11-376	Back	100 mm Al_2O_3

Before and after shooting, the solar cell's current and voltage characteristics were measured using the Xenon Arc Lamp Flash Simulator at the NASA Lewis Research Center. These test measurements included short circuit current (Isc), open circuit voltage (Voc), maximum power current (Imp), and maximum power voltage (Vmp).

After each impact test, most impact sites were identified along with their x/y coordinates. At these sites the crater diameter and surrounding fractured area diameters were measured. During the impact test a high speed camera in the streak mode also recorded the x/y coordinates of each impact along with the time of occurrence, thus providing the projectile velocity. The holes in the Mylar film, located a few inches ahead of the target, were also measured.

The test conducted at MSFC using the light gas gun follows a similar procedure. The individual solar cells and the entire coupon were tested for voltage and current characteristics before and after the impact test. The impact test consisted of firing a 1/4" aluminum sphere which reached a velocity of approximately 7 km/s.

Test Results

The front surface of the solar cells were shot with 100 and 400 micron aluminum oxide and 100 micron olivine particles. The typical impact features on the 8cm X 8cm cells are shown in Figure 1. Most of the features are less than 1000 mm across but a few are in 1000 to 2000 mm range.

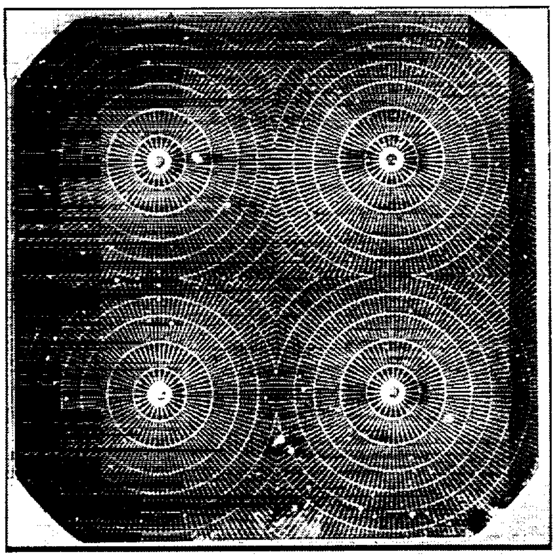

Figure 1, Impact Features on Cell 11-221

One of the larger features on cell 11-221 is shown is Figure 2. The well defined crater to the upper left of center is about 300 microns across. This crater was formed by a particle with a velocity of 5.4 km/s. The morphology of this crater is nearly identical to one reported by E. Schneider for a particle with identical velocity. [2] The spall to the lower right of center of Figure 2 was caused by a second particle impact.

Figure 2, Large Impact Feature on Cell 11-221

Approximately 150 to 200 impact sites were recorded for each cell. Velocities were obtained for about one quarter to one half of the sites. A plot of typical velocities is shown in Figure 3.

The plot shows that velocities generally ranged from 5 to 10km/s. The average velocity for shot C19 was 7.2km/s. Shots C20 and C21 had average velocities of 6.1km/s and 6.0km/s, respectively.

There were a few impacts caused by particles with velocities between 10 and 11km/s. Examination of these sites revealed small clusters of impacts. The respective film penetration were single holes with diameters two or three times larger than the crater diameters. This seems to indicate that the particles with velocities above 8 or 10km/s are fracturing when they pass through the Mylar film.

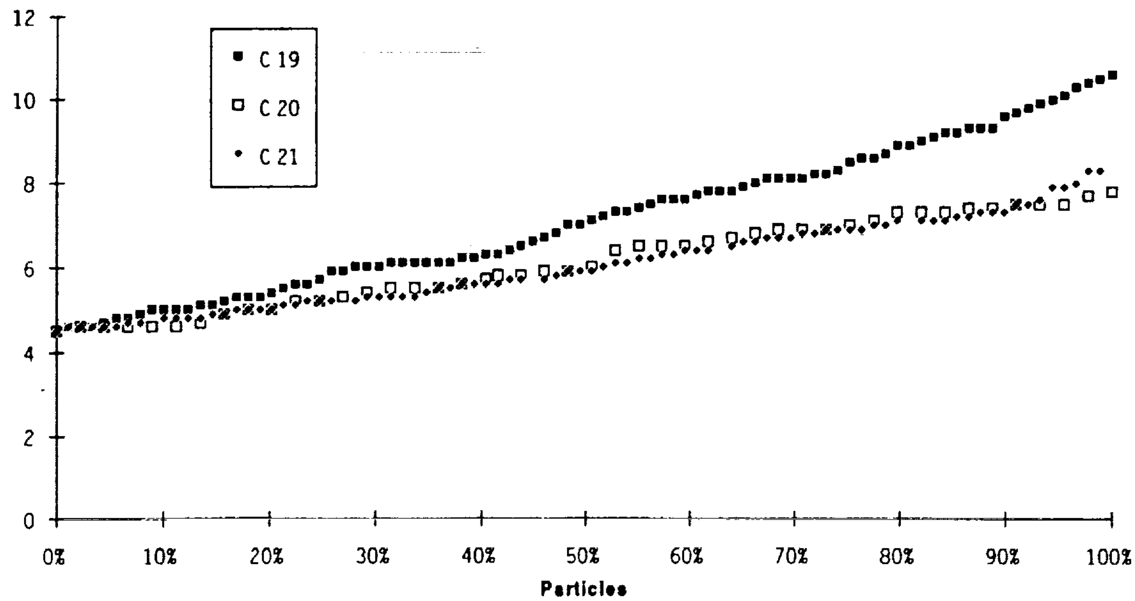

Figure 3, Particle Velocities

To determine the relative damage done to the solar cell, the diameter of the fractured zone surrounding the impact site was measured. These are plotted in Figure 4. The examination of shot C19 shows that most fractured zones are between 200 microns and 700 microns in diameter, the average being 460 microns. The average fractured zone diameter for shots C20 and C21 was 370 microns and 440 microns. The largest fractured zones, i.e. greater than 1000 microns across, often proved to be caused by multiple impacts. The areas of the fractured zones were calculated and summed. Comparing this sum with the total cell surface area indicated that the total fractured area was only .61% for shot C19, .50% for C20, and .57% for C21.

Microscopic examination of the impacts revealed that only one particle had penetrated through the entire cover glass and solar cell but did not penetrate the Kapton layers. A few other impacts penetrated through the cover glass and into but not through the solar cell. Most of the damage was limited to the cover glass.

Where discernable, the diameters of the impact craters were measured along with the penetration hole in the Mylar film. The measurements for shot C19 are shown in Figure 5. The plot shows some correlation between sizes of the impact crater and the film penetration. It also shows that the two are approximately the same size. The average crater diameters for shots C19, C20, and C21 were respectively 51, 56, and 83 microns. The average penetration diameter in the Mylar film were respectively 58, 45, and 48 microns.

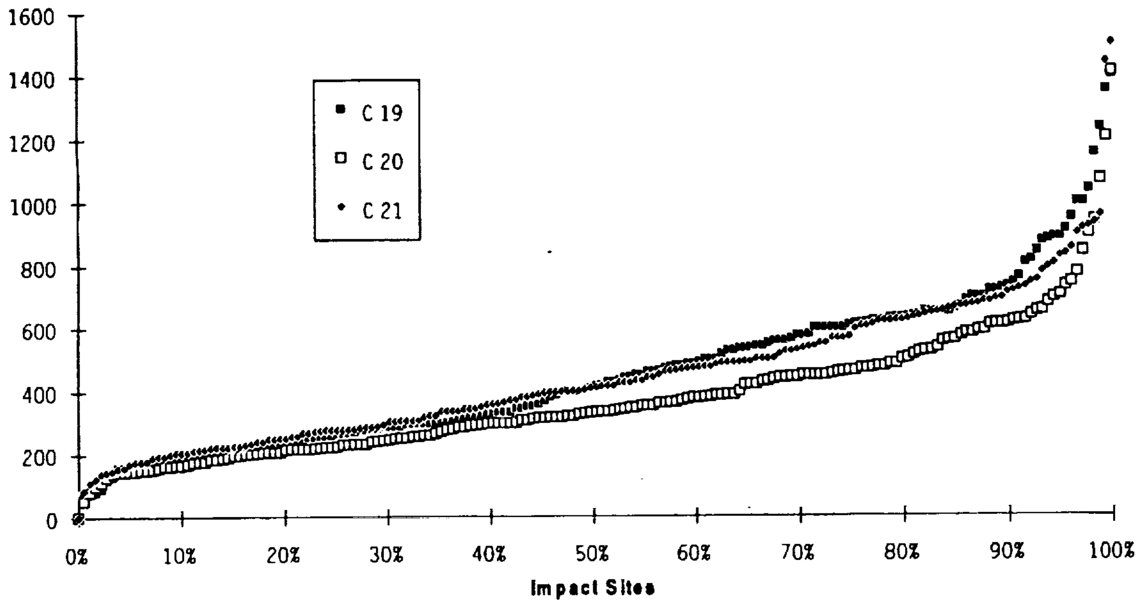

Figure 4, Fractured Zone Diameters

The back surface of cell 11-376 was also shot with 100 micron aluminum oxide. Other than the small penetration holes in the Kapton film and glass scrim cloth, there was no observable damage to the solar cell. During a similar test on solar cells designed for the National Space Telescope (NST) the particles completely penetrated the blanket material and solar cell and created lárge spalls on the front surface. This did not occur with the SSF cells.

At MSFC the impact produced a neat hole approximately 3/8" in diameter as shown in Figure 6. The area of the hole is approximately 0.129 in.^{2} which represents only 1.3% of the total cell area. Although there were a few cracks in the cover glass of the adjacent cells, the propagated damage was minor. The obscured area surrounding the impact hole is contamination deposited during the firing of the gun. The contamination film was assumed to be a residue of melted Lexan[3]. Most of this contamination was cleaned off but a transparent film remained on the surface which covered an area about 1" in diameter.

Discussion

The total amount of damage caused by the 100 to 400 micron particles was very small, less than 1%. Therefore it was not possible to measure any performance loss in the solar cells. Since the total particle impact fluence during the test greatly exceed what the SSF solar arrays will experience during its life, we can anticipate no measurable loss in electrical performance from

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[3] Lexan® is a registered trademark of General Electric Company.

particle impacts of this type. The following table summarizes the results.

	Shot		
	C19	C20	C21
Velocity (km/s)	7.2	6.1	6.0
Fracture Zone (mm)	460	370	440
Crater Dia. (mm)	51	56	83
Film Penetration (mm)	58	45	48
Damaged Area (%)	.61	.50	.57

From these results the following was observed: The 400 micron particles used in shot C20 had the lowest average fractured zone diameters. These particles also had a relatively low average velocity which was similar to shot C21. Furthermore the film penetration diameters indicate that these particles were shattered into particles generally smaller than 100 microns. In general the results indicate that there is a wide distribution in particle sizes and since the average Mylar film penetration diameters are similar for each shot this may indicate that each shot has a similar distribution. Furthermore microscopic (SEM) examination of the projectiles revealed that the initial particles are not spherical but were oblong. The mass of a particular particle could vary from 0.5 to 3.0 times the mass of a spherical one.

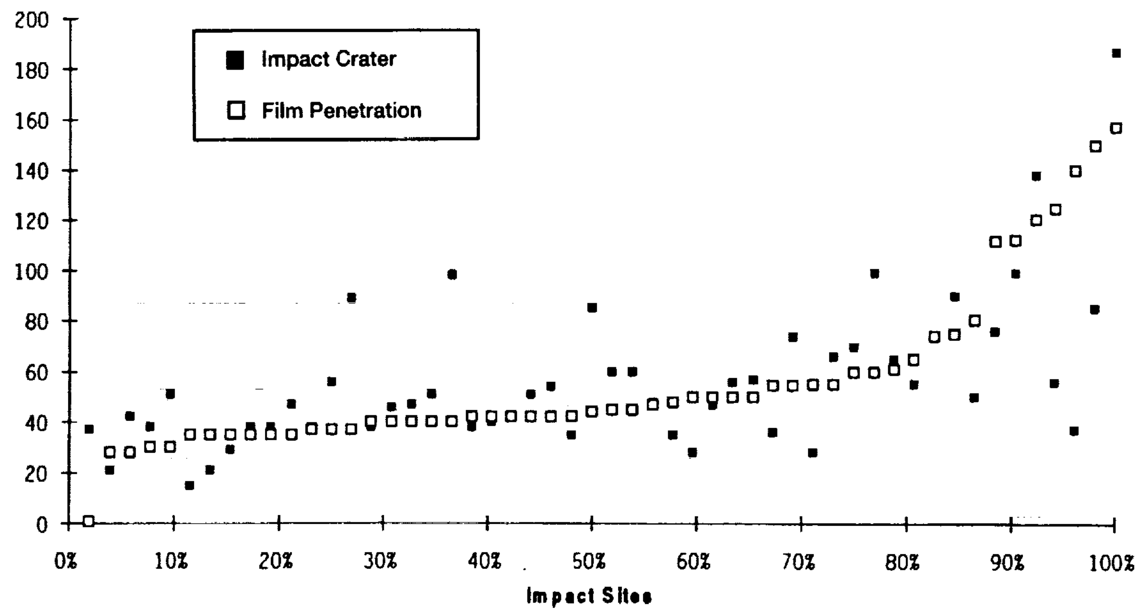

Figure 5, Impact Crater and Film Penetration Diameters

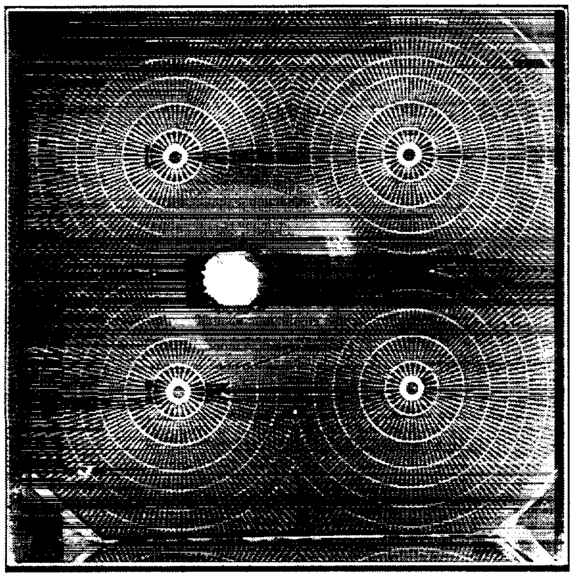

Figure 6, Impact Feature from 1/4" Projectile

The ratio of fracture zone diameter to crater diameter ranged from about 5 to 9. On LDEF these ratios ranged from 5 to 8.[3] The morphology of the craters is also visibly similar.

Even though olivine has a lower density than aluminum oxide the olivine particle impacts appear to have created significantly larger crater diameters. These particles also had a relatively low average velocity, 6.0km/s, but still produced fractured zone diameters similar to shot C19 which had an average velocity of 7.2km/s. Therefore we might conclude that olivine does more damage than aluminum oxide.

Damage from impacts on the back surface of the solar cell was effectively mitigated by the three layers of Kapton film and the glass scrim cloth. This indicates that SSF solar cells are much more robust than those used on the NST.

The 1/4" projectile, shot by the light gas gun at MSFC, had a velocity of approximately 7 km/sec and produced measurable damage.

Before impact the coupon and cell had the following voltage and current characteristics:

	Coupon	Cell
Isc	2.57	2.66
Voc	2.33	0.563
Imax	2.20	2.18
Vmax	1.72	0.381

After impact the I/V characteristics were:

	Coupon	Cell
Isc	2.02	1.89
Voc	2.30	0.523
Imax	1.77	1.55
Vmax	1.77	0.347

The percentage loss is as follows:

	Coupon	Cell
Isc	-21%	-29%
Voc	-1.3%	-7.1%
Imax	-20%	-29%
Vmax	+2.9%	-8.9%

It is interesting to note that although the Voc of the individual cell did drop significantly, the Voc of the 4 cell array (coupon) did not change.

Conclusion

These test have shown that particles in the micron to 100 micron size range with velocity ranging from 4.5 to 10.5 k/ms do not create significant damage to Space Station Freedom solar cells. Therefore there should be no electrical power degradation of the solar arrays due to impacts from these type particles.

Although the 1/4" diameter projectile produced measurable damage the cell and coupon continued to operate. Since the fluence of these size particles is very small the probability of such an impact occurring on orbit is remote.

The 1/4" projectile created a penetration 3/8" in diameter which is only 1.7% of the total cell area but this caused a 35% reduction in maximum power output of the individual cell. Although Imax of the cell dropped 29% the Imax of the coupon only dropped 20%, which resulted in a 17% decrease in power output of the array. This indicates that summing the current losses from individual cells does not equal the total current loss in an array.

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13. ABSTRACT ***(Maximum 200 words)***

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